Astrophysical consequences of a violation of the strong equivalence principle

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A previous analysis of the consequences of a violation of the strong equivalence principle (SEP) for massive particles has now been extended to the case of photons and leads to the prediction that the photon number is conserved. Comparison of the predictions of our theory with observations, especially those on big-bang nucleosynthesis, shows that a violation of the SEP is not ruled out by the data available, and that further direct measurements are required.

THE strong equivalence principle (SEP) states that the outcome of any gravitational or non-gravitational experiment is independent of where and when in the Universe it is performed[1], or, in particular, that in spite of changes in the global distribution of matter in the Universe, no influence is to be felt by local gravitational and non-gravitational experiments performed at different epochs. It can be shown[1] that the SEP requires that all clocks in nature be equivalent, or that the ratio of their intrinsic units of time be constant. An SEP violation occurs when the ratio of the period of an atomic (or nuclear or weak) clock to that of a gravitational clock (such as a planet revolving about a star) is not constant in time. If by Δt_E we denote a time interval recorded with a gravitational clock and by Δt that recorded by an atomic clock, we characterize an SEP violation by a non-null value of the time derivative $\dot{\beta}_a$ of the quantity β_a defined by $\Delta t_E = \beta_a \Delta t$ (refs 1, 2).

The question whether or not the SEP is violated can be resolved directly by observations. For example, by using an atomic clock to record the flight time of photons to and from Mars, one can monitor the period of Mars orbiting the Sun, which is a gravitational clock. The analysis of the radar ranging data would then lead to a determination of $\dot{\beta}_a$ (ref. 3).

To stimulate an observational search to test the SEP, it is necessary to show that an SEP violation is at least not ruled out by data already existing. To carry out the analysis, one needs a theoretical scheme and in particular to know whether an SEP violation would affect both gravitational and non-gravitational physics, as is possible in principle. Before our work, it was generally assumed that an SEP violation would affect only gravitational phenomena and that all non-gravitational physics is independent of it. To be specific, it was assumed that both one- and many-particles relations for fermions and bosons remain independent of β_a even when $\dot{\beta}_a \neq 0$. The prototype of such theories is that of Brans and Dicke.

We have recently constructed an SEP violating framework[1] that does not require that an SEP-violation should affect only gravitational phenomena.

Two main results have emerged. (1) Where massive particles are concerned, while one-particle relations remain unchanged, many-body relations (for example, the relation between pressure P and density ρ) are affected by β_a, in contrast with the assumptions of previous theories where this did not occur. (2) In order for atomic and gravitational clocks to run at different rates, the relation between the gravitational constant G and the function β_a must be of the form $G \sim \beta_a^{-g}$, with $g = 2$.

Our previous work[1] did not deal with photons, but we have now been able to extend it so as to arrive at a framework for photons which is valid for any g. In so doing, we discover that our previous photon theory[4] holds only for $g = 1$. That theory is therefore no longer tenable because it is inconsistent with the condition (2) above that for the SEP to be violated, g must be 2. We stress that the $g = 1$ theory must be abandoned not for observational reasons but on the grounds of theoretical consistency. (The implications of the two photon theories for the 3 K radiation are compared in what follows.)

The new photon theory allows us to construct five new tests of SEP violation. Together with previous tests of a cosmological nature[5,6], we conclude that an SEP violation has been found to be compatible with a wide range of data from astrophysics to geophysics. The results do not prove that an SEP violation must occur, but they constitute the assurance required for an observational search to be undertaken[3]. (As in ref. 1, β denotes general units; in atomic units, AU, $\beta = \beta_a$; in gravitational units, EU, $\beta = 1$).

Photons

Single particle relations: We begin with the derivation of the equation for the propagation of photons using the equation of motion in terms of the four velocity u^α of a test particle[1] of mass μ

$$u^\alpha_{;\nu} u^\nu + \frac{(\mu\beta^{2-g})_{,\nu}}{(\mu\beta^{2-g})} \Delta^{\alpha\nu} = 0 \tag{1}$$

The second term in equation (1), involving the 'projection operator' $\Delta_{\alpha\nu} = u_\alpha u_\nu - g_{\alpha\nu}$ $(\Delta_{\alpha\nu} u^\alpha u^\nu = 0)$ is a deviation from the standard geodesic equation $u^\alpha_{;\nu} u^\nu = 0$, (where the semi-colon denotes the covariant derivative) arising from the possible non-constancy of μ, β and G.

Introducing the momentum $p_\alpha = \mu u_\alpha$ (with $c = 1$), where $p^\alpha p_\alpha = \mu^2$, equation (1) can be rewritten as

$$(\beta^{2-g} p_\alpha)_{;\nu} p^\nu - \tfrac{1}{2}\beta^{g-2}(\beta^{4-2g} p^\nu p_\nu)_{;\alpha} = 0 \tag{2}$$

For zero rest mass particles, $p^\nu p_\nu = 0$, this reduces to

$$(\beta^{2-g} p_\alpha)_{;\nu} p^\nu = 0 \tag{3}$$

which is equivalent to equation (3.10) of ref. 4 if one chooses $g = 1$.

To derive the energy–frequency $(\varepsilon_\gamma, \nu)$ relation, note that the energy of a photon of momentum p^α, as measured by an observer with velocity u^α, is $\varepsilon_\gamma = u^\alpha p_\alpha$. As in the standard case, using a Robertson–Walker (RW) metric, equation (3) implies, for co-moving observers $u^\alpha = \delta^\alpha_0$,

$$p_0 \sim \frac{\beta^{g-2}}{R} \quad \text{and} \quad \varepsilon_\gamma = \delta^\alpha_0 p_\alpha = \frac{h\nu}{\beta^{2-g}} \tag{4}$$

where h is a constant and where we have used the standard redshift relation $\nu R =$ constant, as required by the fact that the photon path is null. The energy–frequency relation (4) can be shown to hold true for a general metric. It can be seen that if $g = 1$, or $G \sim \beta^{-1}$, the relationship $\varepsilon_\gamma = h\nu/\beta$ derived in ref. 4 (equation (3.15)) is recovered.

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Since we have shown[1] that g must be 2, we conclude that the two relations in equation (4) are identical with those of standard theory.

Photons in a beam: Let us now consider a beam of photons described by an energy momentum tensor of the standard form $T_{\alpha\nu} = fu_\alpha u_\nu$ where the function f will be determined later. In our framework, the possible non-constancy of β and G changes the standard conservation law $T^{\alpha\nu}{}_{;\nu} = 0$ to (equation (4.1) of ref. 4)

$$T^{\alpha\nu}{}_{;\nu} + (2-g)\frac{\beta_{,\nu}}{\beta}T^{\alpha\nu} - \frac{\beta^{,\alpha}}{\beta}T^\lambda_\lambda = 0 \qquad (5)$$

With the help of equation (3), we obtain

$$(fp^\nu)_{;\nu} = 0 \qquad (6)$$

To determine the function f, we note that the photon energy density, $\rho_\gamma \equiv n_\gamma \varepsilon_\gamma$, (where n_γ is the photon number density) measured by an observer with velocity u^α, is given by $\rho_\gamma = T^{\alpha\nu}u_\alpha u_\nu = f(p^\alpha u_\alpha)^2 = f\varepsilon_\gamma^2$. Therefore, $f = n_\gamma/\varepsilon_\gamma$. For observers momentarily at rest, so that $u^\alpha = g_{00}^{-1/2}\delta_0^\alpha$ and $\varepsilon_\gamma = p^0 g_{00}^{1/2}$) integration of equation (6) yields

$$\int \sqrt{\hat{g}}\, n_\gamma g_{00}^{-1/2}\, dx^3 \equiv N_\gamma = \text{constant} \qquad (7)$$

where $\hat{g} = |\det g_{\mu\nu}|^{1/2}$. The number of photons N_γ is therefore conserved independently of the value of g.

Furthermore, we find that the cross-section A of the beam satisfies the relation $A_{;\alpha}\beta^{2-g}p^\alpha = A(\beta^{2-g}p^\alpha)_{;\alpha}$, which using equations (4) and (6), yields $n_\gamma A/\nu =$ constant. As in standard theory, this expresses the conservation of the number of photons passing through different cross-sections along the beam.

Adiabatic photon gas: Consider black-body radiation in a box of volume V. Integrating equation (5) with $p = n_\gamma kT = 1/3\rho_\gamma$, one obtains

$$\rho_\gamma \sim \beta^{g-2}V^{-4/3}, \qquad N_\gamma T V^{1/3}\beta^{2-g} = \text{constant} \qquad (8)$$

The photon number N_γ is defined as $n_\gamma V = \rho_\gamma V/\varepsilon_\gamma$. Since the frequency ν of the standing photon waves is related to V by $\nu \sim V^{-1/3}$, it follows that

$$N_\gamma = \text{constant} \qquad (9)$$

independently of g. Therefore, the number of black-body photons in a box is constant independently of whether the SEP is violated or not. We note that the relation $N_\gamma \sim \beta_a^{g-1}$ used in ref. 4 is consistent with equation (9) only if $g = 1$. From equation (8) with the help of equation (9) it follows that

$$\rho_\gamma \sim \beta^{3(2-g)}N_\gamma^4 T^4 \sim \beta^{3(2-g)}T^4 \qquad (10)$$

which reduces to the standard Stefan–Boltzmann relation for $g = 2$.

Black-body radiation spectrum: To obtain the differential spectral density $\rho_{\gamma\varepsilon}$ (with $\rho_{\gamma\varepsilon}\, d\varepsilon = \rho_{\gamma\nu}\, d\nu$ in an obvious notation) we use equation (8) in the form $\beta^{2-g}V^{4/3}\rho_\gamma =$ constant whence (with N_γ constant)

$$\begin{aligned}\rho_{\gamma\varepsilon} &\sim \beta^{3(2-g)}\varepsilon_\gamma^3 f(\varepsilon_\gamma/T)\\ \rho_{\gamma\nu} &\sim \beta^{g-2}\nu^3 f(\nu/\beta^{2-g}T)\end{aligned} \qquad (11)$$

where $f(x)$ is a universal function of x. Putting $g = 1$, the second of equations (11) reduces to equation (5.17) of ref. 4. With $g = 2$, the spectra are identical with standard spectra.

Photons and massive particles: Our conclusion (equation (9)) that the photon number is constant must be contrasted with our earlier result[1] for the particle number N_p

$$N_p \sim \frac{1}{\beta_a G} \sim \beta_a \qquad (g = 2) \qquad (12)$$

what this implies is that while all photon relations are unaffected by the presence of an SEP violation, massive particle numbers are affected. To take the comparison further, consider a system of massive particles described by $T_{\alpha\nu} = (p+\rho)u_\alpha u_\nu - pg_{\alpha\nu}$, where $\rho = \rho_0 + \rho_*$ and $\rho_0 = mn$ where $n = N_p/V$ and $p = \Gamma\rho_* = nkT$. Integrating equation (5), and using the expressions for ρ_0 in equation (4.23) of ref. 4 or equation (2.47) of ref. 7, we conclude that

$$\rho_* V^\gamma \beta^\Omega = \text{constant} \quad \text{or} \quad N_p T V^{\gamma-1}\beta^\Omega = \text{constant} \qquad (13)$$

where $\Omega = 3\Gamma + 1 - g$, $\gamma = 1 + \Gamma$. Eliminating T, one further gets (in AU)

$$p \sim \rho_0^\gamma N_p^{-\gamma}\beta_a^{-\Omega} \quad \text{or} \quad p \sim \rho_0^\gamma \beta_a^{-(\gamma-1)(2+g)} \qquad (14)$$

showing that the p–ρ_0 relation is indeed altered by possible violation of the SEP. Equation (14) was used in ref. 8 to study the problem of the Earth's palaeoradius.

The results of the proceeding calculations may be summarized as follows:

(1) The photon number N_γ and the particle number N_p behave differently as a consequence of an SEP violation. While N_γ is constant as in equations (7) and (9), N_p is not, equation (12), since g must equal 2 if gravitational and atomic clocks[1] are not to be equivalent.

(2) For $g = 2$, all photon relations are unaffected by SEP violation.

(3) Accordingly, SEP violation cannot be detected by the study of free photons, because it affects only the behaviour of massive particles.

Cosmology

In our previous work (see, for example, ref. 5) we have compared the predictions of our earlier calculations with various cosmological data, especially those pertaining to the variation of magnitude or angular diameter with redshift for galaxies (including radiogalaxies) and for QSOs. (The results of refs 5, 6 apply, provided that $g = 2$.) These comparisons show that an SEP violation is not inconsistent with the data provided that $G \sim t^{-1}$ or, equivalently, that $\beta_a \sim t^{1/2}$. We now proceed to a consideration of the implications of our new results.

Age of stars and globular clusters

If G were larger in the past, stellar luminosities would have been great. For the Sun, detailed numerical computations are available in the literature[9–13] for the two cases: $M \sim t^0$ and $M \sim t^2$, where M is the total mass both using $G \sim t^{-1}$. In the first case, the radioactive age of the Sun can be matched if the hydrogen and metal abundances X and Z, respectively are $X = 0.82$ and $Z = 0.017$, whereas for $M \sim t^2$, the required abundances are $X = 0.725 - 0.73$ and $Z = 0.02$. The first set is considered unacceptable, since present estimates of the helium abundance Y are $0.20 \leq Y \leq 0.30$, whereas the second set is clearly acceptable. In the present framework, because of $G\beta_a^2 =$ constant and $\beta_a GM =$ constant (ref. 7), we have $M(t) \sim G^{-1/2}(t) \sim t^{1/2}$, a case intermediate between those investigated numerically so far. The final result must therefore be $0.73 < X < 0.82$, leading to an acceptable helium abundance Y.

For globular clusters, unlike the case of the Sun, the HR diagram provides a well defined turn-off position, and so since a larger luminosity in the past implies a shorter lifetime, one may avoid the difficulties created by an increase in the Hubble constant to 80–100 km s^{-1} Mpc^{-1}, as recently suggested. In fact, such large values would imply a maximum age of the Universe of $10–12 \times 10^9$ yr, lower than the age of some globular clusters computed from standard theory, the estimated age of 15×10^9 yr for M15, for example.

Past temperature of Earth

A larger G in the past implies a higher solar luminosity L and hence a higher effective temperature, T, on the surface of the Earth. Quantitative estimates of the effect, first done by Teller[14] lead to

$$L \sim G^8 \qquad T \sim G^{2.5} \qquad (15)$$

This implies that 4×10^9 yr ago, $T = 500$ K, well above the boiling point of seawater and in apparent contradiction with well substantiated data that liquid water existed on the Earth as long as 3.8×10^9 yr ago. We have used the power law $G/G_0 = t_0/t$, $t_0 = 15\times10^9$ yr as well as the present temperature $T_0 = 250$ K, corresponding to no greenhouse effect. Also included in the estimate of $T = 500$ K is the prediction by standard stellar evolution[15] that 4×10^9 yr ago the Sun's luminosity was 30–40% lower than today, implying an 8% reduction in T.

Within the present framework, the equations for the hydrostatic equilibrium equation, the radiative transfer and stellar luminosity ($L = \varepsilon M$, where $\varepsilon \sim \rho T^n$ is the nuclear energy rate[9–13]) and the equations of state $pV = N_p kT$, $\rho_\gamma \sim T^4$, together with $G = G(t)$ and $M \sim G^{-1/2} \sim \beta_a$ yield by homology arguments

$$L \sim G^\alpha M^\delta \sim G^{s/2} \sim \beta_a^{-s}$$

where

$$s = 2\alpha - \delta = \frac{59+18n}{5+2n} \tag{16}$$

With $n = 4$ for the Sun, and remembering that the Earth–Sun distance D scales like $D_0 = \beta_a D$, we derive

$$L \sim G^5 \qquad T \sim G \tag{17}$$

which implies that 4×10^9 yr ago, $T \approx 313$ K, well below the boiling point of seawater.

Although a fully reliable result must await an atmospheric calculation as well as the evaluation of the L–G relation based on a detailed stellar evolutionary model, the estimates presented here indicate the contrast with the results obtained from previous quantifications of the SEP violation. Predictions of "boiling oceans", which contradict existing data, do not arise in the present model. (For the predictions of the Brans–Dicke theory see ref. 16.)

3-K Black-body radiation

The black-body radiation has long been considered of crucial importance to SEP violating theories. One important consideration must be stressed—*a priori*, it is not known whether an SEP violation requires the standard particle conservation law be changed and if so, whether photons and massive particles are equally affected.

The first theory implementing an SEP violation, that of Jordan[17], made no predictions on this problem, thus leaving the question to be settled by observational data. In 1968, Honl and Dehnen[18] showed that a non-constant photon number N_γ would be incompatible with the 3 K black-body spectrum. Whereupon Jordan[19], acknowledging the impossibility of reconciling his theory with variable N_γ, suggested that the other version of his theory with constant N_γ be adopted. (This coincides with the Brans–Dicke theory.)

Perhaps unaware of the 1968 results, Dirac in 1972, 1973 and 1975 stated[20–22] that a variable N_γ cannot be reconciled with the 3 K radiation. The same conclusion was reached by Canuto and Lodenquai[23] in 1977 in an attempt to test an SEP violation by the use of observational data. In 1978, again unaware of the 1968 work, Steigman[24] arrived at the same conclusion as Honl and Dehnen, namely that a non-constant N_γ is not compatible with the 3 K radiation.

Thereafter Canuto and Hsieh proposed two alternative solutions of the 3 K problem. In 1978, it was shown[25] that if instead of the gauges $G \sim \beta_a^{\pm1}$, ($G \sim t^{-1}$) previously used until then by Dirac, Jordan and so on, one chose (1) $G \sim \beta_a^{-2}$ together with (2) $\varepsilon_\gamma \sim \nu$ and (3) $T \sim R^{-1}$, the resulting N_γ was constant and that the 3 K radiation does not exclude a violation of the SEP. However, since the necessary conditions (1)–(3) were assumed, not derived from a complete photon theory, it could not be claimed that the 3 K problem had been solved. In 1979, a complete photon theory was presented[4] in which the propagation equation, the single particle relations and the thermodynamic relations were all derived in a consistent manner. The result was that the 3 K radiation is compatible with an SEP violation provided (1) $N_\gamma \sim \beta_a^{g-1}$, (2) $\varepsilon_\gamma \sim \nu/\beta_a$ and (3) $T \sim \beta_a^{-1}R^{-1}$.

In 1982, however, it was first realized[1] that a violation of the SEP demands $g = 2$. Since the photon theory of ref. 4 has been shown here to be valid for $g = 1$, (in spite of the original belief that it held for any g), the theory is no longer tenable. Unlike Jordan's theory, the 1979 photon theory has to be abandoned, not because of observational reasons but because of theoretical consistency requirements.

In the theory presented here, we have shown that N_γ remains constant for any g and that for the required value $g = 2$, all photon relations are identical with the standard ones. Photons are therefore unaffected by an SEP violation, and the 3 K radiation imposes no constraints on our formulation of the SEP violation.

Finally, we note that both Jordan's theory with variable N (both N_γ and N_p), and that of Brans–Dicke with both N_p and N_γ constant, are not viable, although for different reasons. Our theory, with N_γ = constant, but $N_p \neq$ constant, has thus far not encountered such difficulties.

Nucleosynthesis

The nucleosynthesis of light elements has been a most valuable tool to probe the early Universe[26], and attempts have been made to use the ^{4}He abundance to set limits on the violation of the SEP, expressed phenomenologically as a variable G.

The most recent study[27] indicates that if the shape of β_a as a function of t determined from the matter era is extrapolated to the radiation era, unacceptable values of ^{4}He are obtained. Indeed, the nucleosynthesis data demand an almost constant β_a during the radiation dominated era, and for good reasons. The function β_a represents a cosmological influence on local physics[1,2]. The dynamics of β_a is therefore determined by the global structure of the Universe which in turn is governed by the energy density (and pressure) of matter and radiation. Since matter is affected by β_a, equations (12)–(14), while radiation is not, it is plausible that during the matter-dominated era, the rate of variation in β_a is comparable with the rate of expansion—that is $\dot\beta_a/\beta_a \sim 1/t$, or $\beta_a \sim t^{-n}$, with $n \sim 1$. However, during the radiation era, such a variation is expected to have been considerably smaller, that is, $\dot\beta_a/\beta_a \ll 1/t$, since the dynamical part played by matter was negligible. In such a case, the value of β_a during the short radiation period would not have differed significantly from, say, the last 'matter-dominated' value at decoupling. Indeed, the main result of ref. 27 is that during the radiation era $\dot\beta_a/\beta_a \ll 1/t$, that is $\beta_a \sim t^{-n}$, $n \ll 1$.

We shall therefore propose that during the radiation era, β_a was essentially constant and investigate the consequences for nucleosynthesis. Using the standard framework, Olive *et al.*[28] have recently analysed the dependence of the calculated abundances on the most relevant parameters namely, (1) the baryon to photon number ratio $\eta = n_B/n_\gamma$ which in standard cosmology is equal to its present value $\eta_0 = \rho_{B0}\,10^{22}\,(2.7/T_0)^3/6.64$, where ρ_{B0} is expressed in g cm^{-3}, (2) the neutron half life $\tau_{1/2}$, and (3) a speed-up factor ξ, defined by $\dot R/R = \xi(\dot R/R)_{\text{standard}}$.

In the SEP violating framework, a constant β_a affects nucleosynthesis in two ways. Because of $N_p \sim \beta_a$, we have $n_B \sim \beta_a R^{-3}$, while $n_\gamma \sim R^{-3}$. Therefore $\eta = \eta_0\beta_a$. Furthermore, the RW equation[5], with $G\beta_a^2$ = constant and $k = 0$ becomes

$$\frac{\dot R}{R} = \beta_a^{-1}\left(\frac{8\pi G_0}{3}\rho_\gamma\right)^{1/2} = \beta_a^{-1}\left(\frac{\dot R}{R}\right)_{\text{standard}}$$

so that β_a^{-1} plays the part of a speed up factor ξ.

In Fig. 1 the calculated ^{4}He (Y) and D (D) abundances are plotted as a function of η_0, for the standard ($\beta_a = 1$) and the present theory. In both cases, $N_\nu = 3$ and $\tau_{1/2} = 10.6$ min. The standard model ^{4}He and D abundances were taken from refs 28, 29 respectively. The ^{4}He and D abundances corresponding to the present model were calculated from Fig. 2*a* of ref. 28 using $\xi \equiv \beta_a^{-1}$, and $\eta = \eta_0\beta_a$ and from Table 1 of ref. 29 (the D abundance is a function of $\eta/\xi = \eta_0\beta_a^2$, ref. 29). We first consider the results of the standard case. Determinations of the ^{4}He abundance Y in recent years have limited the uncertainty to the range $0.25 \geq Y \geq 0.20$, corresponding to $4.5\times10^{-11} \leq$

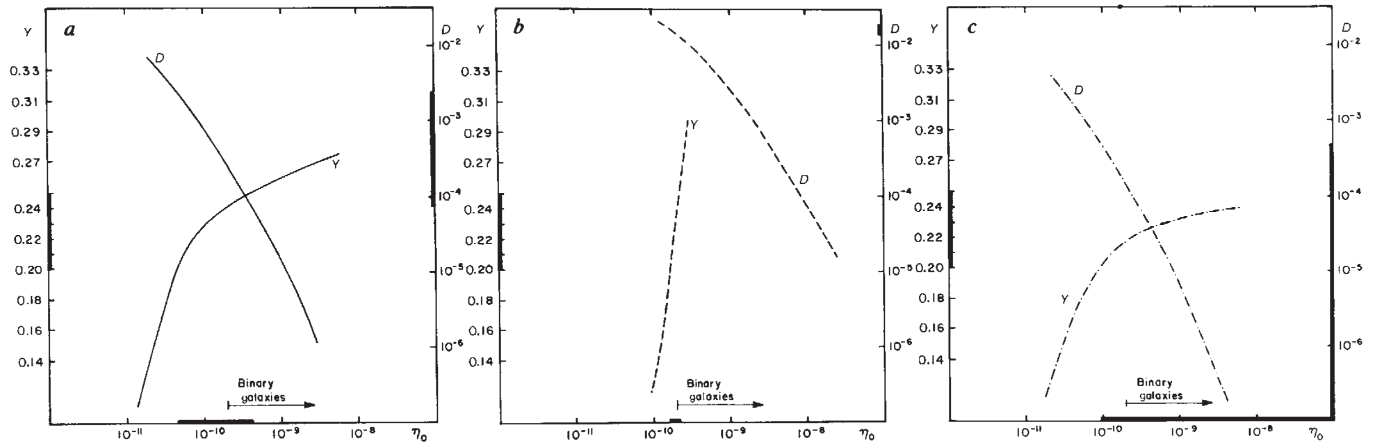

Fig. 1 Predicted helium (Y) and deuterium (D) abundances by mass. Given the range of observed values of Y, one determines the corresponding baryon to photon number ratio η_0. This in turn is projected under the D curve and a D abundance is arrived at, which is then compared with observations. If one accepts the most recent D abundances $7.0\text{–}3.4\times10^{-5}$ (ref. 42) it is seen that the $\beta_a = 1.2$ case fits the data better than the standard case $\beta_a = 1$. a, $\beta_a = 1$; b, $\beta_a = 0.2$; c, $\beta = {}_a1.2$.

$\eta_0 \leq 4\times10^{-10}$. This in turn implies that the D abundance must be $8\times10^{-5} \leq D \leq 2.5\times10^{-3}$. The presently observed D abundance is estimated[30] to be in the range $1\text{–}4\times10^{-5}$, an interval which may still be consistent with that given above since it must be a lower limit because D is in fact only destroyed by stellar processes. The quantification of the destruction is difficult. On the one hand, Rana[31] has concluded that the primordial D abundance must have been $\sim<6\times10^{-5}$, implying that the standard framework is inconsistent. On the other hand, Yang *et al.*[32] and Steigman[30] have argued that since D is converted into ^{3}He, the combined D + ^{3}He should not be less than its present value. This leads to $\eta_0 \geq 2\times10^{-10}$, which in turn corresponds to a D abundance $\leq 2.5\times10^{-4}$, in agreement with the range previously determined. Even if this second solution is accepted, there may be a further problem. Recent data[28,33] on the ^{4}He abundance have suggested values as low as 0.22, implying a D abundance $>1.4\times10^{-3}$, a value which may be difficult to accommodate[34,35]. (Note that the lower the ^{4}He abundance, the higher the D abundance.)

Finally, another potential source of inconsistency stems from the constraint[28] $\eta_0 \geq 2\times10^{-10}$, reached by considerations of dynamics of binary galaxies and small groups of galaxies. This value implies $Y \geq 0.24$, in contradiction with $Y = 0.22$, should this last value be confirmed by future observations. (Here too, a solution has been proposed[28,30]: massive neutrinos, which by contributing to the masses of galaxies would allow a lower value of η_0 due to baryons and so a lower Y).

In conclusion, while it is premature to claim that inconsistencies have been found, it may turn out to be difficult to accommodate Y, D and the constraints of galaxy dynamics within the standard SEP conserving framework.

In the present framework, and on the basis of available lunar data, suggesting $\dot{\beta}_a > 0$, we assume that β_a is monotonically increasing during the matter-dominated era. We have suggested a constant β_a in the radiation era. If β_a behaves monotonically during the radiation to matter transition period, then the constant value must be less than its present value and presumably not very different from its value at the transition time. It is, however, possible that the change of scenario during the transition period and the different behaviour of matter and radiation as a function of β_a, may have caused a non-monotonic behaviour during the transition period, thus allowing for a constant greater than unity value throughout the radiation dominated epoch. The implications for nucleosynthesis of these two alternatives were examined by considering two representative values of β_a, namely $\beta_a = 0.2$ and $\beta_a = 1.2$ (see Fig. 1).

$\beta_a = 0.2$. Repeating the same arguments as in the standard case, we see that the inconsistency between $\eta_0 \geq 2\times10^{-10}$ (binary galaxies) and $Y = 0.23$, no longer exists. The predicted value of D would be about 10^{-2}, a factor of 10 larger than the value predicted by the standard framework if indeed $Y = 0.23$.

$\beta_a = 1.2$. In this case, all the demands for low Y, D and η_0 (binary galaxies) can be satisfied and no inconsistencies arise. For $Y = 0.22\text{–}0.23$, η_0 is required to lie between $2\text{–}6.5\times10^{-10}$, in agreement with the limit contained from binary galaxies. At the same time, D would be $0.1\text{–}1.5\times10^{-5}$, again in agreement with the present data.

Comparison with previous schemes

Two features that differentiate our framework from previous SEP violating schemes are important.

First, they generally assume that (in AU) a violation of the SEP will affect only gravitational physics while leaving all non-gravitational relations unaffected. In the present theory, gravitational physics is affected by β_a but so are the non-gravitational many-body relations for massive particles; for massless particles, all relations are independent of β_a. (This results in a different G dependence of several of the tests, leading in general to a weaker dependence on G, see equation (17)).

The second, and perhaps more important difference is that the present theory allows $\dot{\beta}_a/\beta_a \sim \Lambda H_0$, with $\Lambda \sim 1$, which is a violation of the SEP of the order of the Hubble constant, as expected on physical grounds for a violation of cosmological origin. By contrast, $\Lambda \sim 1$ cannot be achieved in other SEP violating theories, where it turns out that $|\Lambda| \leq 10^{-3}$. (In the Brans–Dicke theory[26], $\Lambda \sim (\omega+2)^{-1}$ and[36] $\omega > 500$; in the Rosen theory[37], $\Lambda \sim \alpha_2$ and[38] $|\alpha_2| \leq 10^{-3}$).

Conclusions

We have attempted to test a possible SEP violation against already existing data, in the hope of providing an incentive for a direct experimental test. To that end, we have constructed a theoretical framework in which the SEP violation is represented by a function β_a treated phenomenologically, that is not provided by the theory itself, much as viscosity or heat conduction coefficients are treated in classical fluid dynamics. The implications of β_a on gravitational and non-gravitational phenomena are then checked against observational data ranging from astrophysics to geophysics and limitations on the variability of β_a arrived at.

Specifically, we have constructed a scale covariant (unit independent) formalism[7], a mathematical procedure that *per se* does not introduce new physics, in much the same way that coordinate covariance requirement does not[39,40]. In our case the physical input occurs when we define the properties that characterize gravitational as different from atomic units. (See ref. 1 for the definitions of the two units.)

In our previous paper[1], we showed that an SEP violation occurs when atomic and gravitational clocks run at different rates, which occurs provided that (1) the relation between the function β_a and the gravitational coupling G is $G\beta_a^2 = \text{constant}$ and that (2) the equations of motion of microscopic particles are different from those of macroscopic bodies. This last property implies that one- and many-body systems respond differently to an SEP violation. In fact, while one-particle relations are unchanged, many-body relations for massive particles depend on β_a (equations (12) and (14)).

Our present treatment of massless particles under an SEP violation shows that the photon number N_γ is conserved and that because of the relation $G\beta_a^2 = \text{constant}$, all photon relations (single and many-body) are unaffected by β_a—they coincide with the standard expressions. The physical implication of this result is that a system of free photons cannot reveal the possible existence of an SEP violation, a result important for the study of the 3 K black-body radiation and nucleosynthesis in the radiation dominated era.

Using the earlier results for massive particles[1], together with those obtained here, our compatibility tests ranging from nucleosynthesis to the radius of the Earth 400 Myr ago[8], show that all the data we have analysed are consistent with an SEP violation of the order of the Hubble constant during the matter dominated era, $\dot{\beta}_a/\beta_a \sim 1/t$, and with $\dot{\beta}_a/\beta_a \ll 1/t$, during the radiation dominated era.

Thus our conclusion that an SEP violation while not demanded is compatible, will hopefully stimulate a direct experimental search using the best data available—the Viking data[2,3,41].

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Embryonic lethal mutation in mice induced by retrovirus insertion into the $\alpha 1$(I) collagen gene

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Experimental insertion of a retrovirus into the germ line of mice has resulted in an embryonic recessive lethal mutation. Integration of the proviral genome occurred at the 5′ end of the α1(I) collagen gene, leading to a complete transcriptional block. Developmental arrest of embryos homozygous at the mutated allele coincides with high expression of the gene in normal embryogenesis. Insertion mutagenesis by retroviruses may offer a general approach to the identification and isolation of genes which are transcriptionally active during mammalian development.

THE phenotypic analysis of experimentally induced or spontaneous mutations has long been the subject of developmental genetics in the mouse[1]. Lethal mutations have had a significant role in identifying pleiotropic effects of presumably single genes on complex developmental processes. Examples of such genetic systems are the well-studied *T* locus[2], the albino deletions[3] or mutations affecting fetal haematopoiesis[4]. This descriptive approach, however, has its limitations in elucidating the underlying developmental defect on a molecular basis, as a randomly mutated gene or its gene product is difficult to identify. An alternative approach to induce mutations by transposable elements, which permits the isolation of the mutated gene by using the element as a tag for molecular cloning, has been used successfully in prokaryotes[5], yeast[6] and *Drosophila*[7].

We have used retroviruses as insertion mutagens to study gene regulation in early mouse development. The Moloney leukaemia virus (M-MuLV) genome was inserted into the germ line by exposing early mouse embryos to virus[8–10] or microinjecting cloned DNA into zygotes[11]. Most of the resulting substrains of mice (Mov-1 to Mov-13 strains) each carry a single provirus at a different mendelian locus[10] and the Mov-14 strain carries a tandem array of multiple proviral genomes[12]. Virus integration at 13 different loci did not lead to a recognizable mutation in the respective animals. Virus insertion at the *Mov-13* locus, however, resulted in a recessive lethal mutation and early embryonic death[13]. All embryos homozygous for viral integration at this locus (*Mov-13/Mov-13*) were arrested in development between days 11 and 12 and died between days 13 and 14 of gestation. Using the virus as a probe, the genomic region of virus insertion was molecularly cloned and shown to represent a unique DNA sequence (ref. 13 and K.H., unpublished). We describe here the activation of the *Mov-13* locus

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